

Spectropolarimetry of FIRST BAL QSOs¹

M. S. Brotherton, Hien D. Tran, Wil van Breugel

Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory,
7000 East Avenue, P.O. Box 808, L413, Livermore, CA 94550; mbrother@igpp.llnl.gov,
htran@igpp.llnl.gov, wil@igpp.llnl.gov

Arjun Dey

KPNO/NOAO², 950 N. Cherry Avenue, P. O. Box 26732, Tucson, AZ 85726; dey@noao.edu

Robert Antonucci

Physics Department, University of California at Santa Barbara, Santa Barbara, CA 93106;
ski@ginger.physics.ucsb.edu

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ABSTRACT

We present Keck spectropolarimetry of two rare low-ionization broad absorption line (BAL) QSOs, FIRST J084044.5+363328 and FIRST J155633.8+351758, that also exhibit narrow absorption lines from metastable excited levels of Fe II (“Iron Lo-BALs”). These QSOs were discovered in optical follow-ups to a deep radio survey; FIRST J155633.8+351758 is radio-loud, the first BAL QSO so identified.

FIRST J084044.5+363328 is highly polarized and exhibits many features found in other BAL QSOs. The continuum is $\approx 4\%$ polarized near 2000 \AA rest-frame, falling to $\approx 2\%$ at longer wavelengths, at a position angle of $\approx 50^\circ$. The emission lines are unpolarized. The polarization rises to $\approx 8\%$ in the low-ionization troughs of Mg II $\lambda 2800$ and Al III $\lambda 1860$. The polarization and its position angle vary in a complicated manner across the metastable Fe II absorption lines, suggesting that more than one mechanism is at work, or that the system geometry is complex.

FIRST J155633.8+351758 may be the most highly polarized BAL QSO known, and exhibits other unusual polarization properties compared to other highly polarized BAL QSOs. The continuum is $\approx 13\%$ polarized near 2000 \AA rest-frame, falling to $\approx 7\%$ at longer wavelengths, at a position angle of 153° . The emission lines are polarized like the continuum, but in the absorption troughs the polarization drops to zero. Currently available data cannot yet discriminate among the possible lines of sight to BAL QSOs (edge-on, pole-on, or random).

Subject headings: quasars: absorption lines, quasars: emission lines, quasars:

general, quasars: individual (FIRST J084044.5+363328), quasars: individual
(FIRST J155633.8+351758), polarization

1. Introduction

Becker et al. (1997) reported the discovery of two unusual low-ionization broad absorption line (BAL) QSOs, FIRST J084044.5+363328 (hereafter 0840+3633, at $z = 1.238$) and FIRST J155633.8+351758 (hereafter 1556+3517 at $z = 1.497$)³, from programs to obtain optical spectra of radio-selected QSO candidates from the VLA FIRST Survey (Becker et al. 1995). Both BAL QSOs exhibit narrow absorption lines from metastable excited levels of Fe II and Fe III like Q 0059–2735 (Hazard et al. 1987), the prototype of this rare class (“iron Lo-BAL” QSOs, as coined by Becker et al. 1997). Furthermore, FIRST 1556+3517 qualifies as “radio-loud,” the first BAL QSO so identified.

Egami et al. (1996) presented near-IR spectra of Q 0059–2735 and Hawaii 167 (see also Cowie et al. 1995), a high- z iron Lo-BAL QSO found in a deep K band survey. Both are red (Q 0059–2735 has $B - K = 3.4$, Hawaii 167 has $B - K = 5.25$), and have large Balmer decrements ($H\alpha/H\beta = 7.6$ and 13, respectively). Egami et al. argued that the implied reddening was so high that much of the rest-frame UV light must arise from scattered light or from a starburst. In Hawaii 167 there is evidence for a 4000 Å break and no UV emission lines are apparent, supporting the latter claim. Near-IR photometry shows that the FIRST BAL QSOs are also red (Hall et al. 1997): FIRST 0840+3633 only modestly so ($B - K = 3.29$), similar to Q 0059–2735, but FIRST 1556+3517 ($B - K = 6.57$) is among the reddest QSOs known. Low-ionization BAL QSOs appear moderately reddened compared with high-ionization BAL QSOs (Sprayberry & Foltz 1992), so perhaps it is not surprising that these highly absorbed iron Lo-BAL QSOs are red.

BAL QSOs are a highly polarized subclass of high luminosity AGN. Hines & Schmidt

³We adopt these redshifts based on comparing our spectra with composite QSO spectra, but an unambiguous redshift is difficult to obtain.

(1997) find that 9 of 28 BAL QSOs have a broadband optical polarization of 2% or greater compared to only 2 of 115 radio-quiet non-BAL QSOs. Spectropolarimetry has been published for about ten BAL QSOs, including Lo-BAL QSOs (e.g., Schmidt, Hines, & Smith 1997; Ogle 1997; Hines & Wills 1995; Cohen et al. 1995; Goodrich & Miller 1995; Glenn et al. 1994). The polarimetric properties are similar from object to object: continuum polarization as high as 5%, increasing toward shorter wavelengths, less polarized or unpolarized emission lines, and absorption troughs with polarizations greater than or equal to the continuum. These results have often been interpreted in terms of orientation (Hines & Wills 1995; Cohen et al. 1995; Goodrich & Miller 1995): BAL QSOs are normal QSOs seen along a line of sight skimming the edge of an obscuring torus, with BAL clouds accelerated from the surface of the torus by a wind, and polarized continuum light scattered above the torus along a less obscured path. Lo-BAL QSOs are then QSOs seen along the most absorbed and dusty lines of sight.

We report spectropolarimetry of the iron Lo-BALs FIRST 0840+3633 and FIRST 1556+3517.

2. Observations and Results

On U. T. 1996 December 10, we observed FIRST 0840+3633 with the Low Resolution Imaging Spectrometer (Oke et al. 1995) in spectropolarimetry mode (Goodrich, Cohen, & Putney 1995) on the 10 meter Keck II telescope. We used a 300 line mm^{-1} grating blazed at 5000 Å, that, with the 1 " slit (at the parallactic angle), gave an effective resolution of 10 Å (FWHM of lamp lines); the dispersion was 2.5 Å pixel^{-1} . The seeing was $< 1''$. The observation was broken into four 5 minute exposures, one for each waveplate position (0° , 45° , 22.5° , 67.5°). Although we observed our calibration standards with and without an order-blocking filter, we did not so observe the QSO, and the red end of the spectrum

is weakly contaminated by second order light. We observed FIRST 1556+3517 on U. T. 1997 April 9 with the same set-up and conditions, and a exposure time for each waveplate position of 15 minutes. We used standard reduction techniques inside the IRAF NOAO package and the procedures of Miller, Robinson, & Goodrich (1988) for calculating Stokes parameters and errors. Table 1 and figures 1 and 2 give the results.

FIRST 0840+3633 is a highly polarized BAL QSO and shares many of the characteristics of previously studied BAL QSOs (e.g., Glenn et al. 1994; Goodrich & Miller 1995; Cohen et al. 1995; Hines & Wills 1995). These include: a polarized continuum with the polarization increasing toward shorter wavelengths (from 2% to 4%), unpolarized emission lines (although C III] λ 1909 may be polarized), and increased polarization in the Lo-BAL troughs of Al III λ 1860 and Mg II λ 2800 (up to 8%). The continuum polarization position angle is about 50° although some rotation may be present in the absorption troughs. The polarization structure is complex across the blended narrow absorption-line troughs that include lines of metastable Fe II and other species. The polarization rises (only to $\approx 4\%$) in the Fe II λ 2750* and Fe II λ 2600* troughs, consistent with reduced source coverage compared with the Lo-BAL troughs (less diluting light is absorbed). The trough of Fe II λ 2380* shows a drop in polarization and a significant position angle rotation. The weaker absorption features do not show significant polarization changes relative to the continuum.

FIRST 1556+3517 is also highly polarized, but differs in its polarization characteristics from other BAL QSOs. The only common behavior is the rise in polarization toward shorter wavelengths (from 7% to 13%), and even this is sharper than common. The level of polarization is remarkable, among the highest seen for a BAL QSO continuum polarization. The polarization of the emission lines (most clearly seen for the prominent Fe II blend at 2950 Å rest-frame) is the same as the continuum; in other BAL QSOs, the emission lines

are less polarized or unpolarized. The polarization drops in the absorption line troughs, apparently to zero in the low-ionization BALs and in the stronger blended Fe II troughs. In almost all other BAL QSOs, the trough polarization is the same as or greater than that of the continuum.

3. Discussion

3.1. The Polarization

Scattering by either dust or electrons probably produces the continuum polarization in both FIRST 1556+3517 and FIRST 0840+3633, as has been suggested for other BAL QSOs. Both are at high Galactic latitudes and have polarization wavelength dependences inconsistent with polarization by transmission through aligned grains in our galaxy or in their host galaxy (e.g., Goodrich & Cohen 1992 and references therein). FIRST 1556+3517, while radio-loud and having a flat radio spectrum (Becker et al. 1997), shows polarization of its emission lines at the same level and position angle as the continuum, ruling out synchrotron radiation as the origin for the polarization.

A rise in polarization toward shorter wavelengths, especially for wavelengths near 2000 Å rest-frame, is predicted by a number of dust scattering models (e.g., Kartje 1995). The rise may also result from the combination of wavelength-independent scattering by electrons or small dust grains, plus dilution by some redder component. In the case of FIRST 0840+3633, the polarization shape probably represents dilution by unpolarized emission from extensive Fe II blends (Wills, Netzer, & Wills 1985), as the polarization rises again at the red end of our spectrum (Table 1).

The deep absorption troughs of FIRST 1556+3517 are unpolarized, indicating that the scattered light is completely absorbed; Markarian 231, which has strong absorption (but

which is not broad enough to qualify as a BAL under the strict but somewhat arbitrary definition of Weymann et al. 1991), also has a powerful starburst and shows a decrease in the polarization in its absorption troughs (Smith et al. 1995). The trough light of FIRST 1556+3517 is probably emitted by an underlying stellar component, or by direct reddened QSO light. The shape of the unpolarized spectrum filling in the trough bottoms, if interpolated between the troughs, is indeed red, but at too low a level to account for the dramatic change in the polarization. The trough light is $\sim 10\%$ of the flux near C III] $\lambda 1909$. If essentially all the light near C III] $\lambda 1909$ is scattered except for this unpolarized trough component (i.e., the scattering polarization efficiency is 90%), then approximately half the light at the red end of our spectrum is scattered. A directly viewed FIRST 0840+3633-shaped QSO spectrum can account for this dilution if reddened by $A_V \sim 2.5$, or an average QSO spectrum if reddened by $A_V \sim 3$ (with an SMC-type extinction and $R = 3.1$). Dilution and wavelength-dependent dust scattering may both be present, but we cannot distinguish between these with current data.

Because the emission lines in FIRST 1556+3517 are polarized identically to the continuum, we place the scattering medium well outside the broad-line region (e.g., ~ 1 parsec for this luminosity). This is in contrast to most BAL QSOs for which the scattering medium must be coincident or smaller than the broad-line region (e.g., Cohen et al. 1995).

Resonance line scattering may contribute to the polarization, and may explain the polarization of C III] $\lambda 1909$ (as in PHL 5200, Cohen et al. 1995), and the change in polarization and the position angle rotation in the troughs in FIRST 0840+3633. The rise in polarization in the FIRST 0840+3633 Lo-BAL troughs may more simply indicate that the scattered continuum is less absorbed than the unpolarized, diluting continuum.

Wampler et al. (1995) analyzed the individual broad and narrow absorption lines in a high-resolution spectrum of Q 0059–2735 and concluded that there are low-ionization

condensations in a hotter BAL flow which occult different parts of the background emission regions. Thus it is probably not surprising to see complex changes and rotations in the metastable absorption troughs of FIRST 0840+3633. There is no systematic relationship between excitation energy and trough polarization for the metastable Fe II troughs, so a simple geometry is not evident. A high-resolution spectrum is required for further progress.

3.2. The Geometry

Given axisymmetry based on other classes of AGNs and the prospect of a radio jet axis, BAL QSOs may be seen along three possible lines of sight:

1. An *edge-on* “torus-skimming” line of sight.
2. A *pole-on* line of sight.
3. *Random* lines of sight.

A primary discriminant between geometries is that edge-on systems are expected to have higher polarizations than pole-on systems. High- z BAL QSOs are highly polarized as a class (Ogle 1997; Hines & Schmidt 1997) while high- z non-BAL QSOs are not (Antonucci et al. 1996). This provides statistical support for an edge-on geometry for BAL outflows. The high polarization in the FIRST iron Lo-BALs QSOs also suggests an edge-on geometry, and the polarization wavelength dependence resembles that of edge-on dust scattering models (Kartje 1995). It is therefore natural to propose that iron Lo-BAL QSOs fit into unified models as the most edge-on QSOs.

The jets of radio-loud QSOs permit another way to measure their orientation. The relativistic beaming model for radio sources (e.g., Orr & Browne 1982) unifies core-dominated (flat spectrum) and lobe-dominated (steep spectrum) radio sources by

means of orientation: core-dominant objects are those viewed close to the jet axis, while lobe-dominant objects are those viewed at larger angles.

The combination of radio-selected BAL QSOs (for which a radio jet orientation can be obtained) with high optical polarization (with a polarization position angle) can eventually be used to test geometries. The position angle rotation caused by resonance line scattering in 0226–1024 indicates that the scattering medium is distributed perpendicular to the BAL outflow (Ogle 1997). While the relationship between the radio axis and the polarization axis is model dependent, in lower luminosity AGNs, “face-on” Seyfert 1 galaxies have optical polarizations with position angles parallel to their system axes, while “edge-on” Seyfert 2 galaxies generally have polarization position angles perpendicular to their jet axes (e.g., Antonucci 1993).

FIRST 1556+3517 has a flat and variable radio spectrum and is unresolved in FIRST survey images (5"), suggesting the radio axis is pointed close to the line of sight. This object may represent a relativistically boosted radio-quiet QSO (e.g., Falcke, Sherwood, & Patnaik 1996), with BAL flow along the jet axis, a very different geometry from currently popular models. The radio spectra of radio-quiet BAL QSOs show a variety of shapes, including both flat and steep spectra, with properties similar to those of radio-quiet and radio-loud QSOs (Barvainis & Lonsdale 1997), suggesting that BAL QSOs are randomly oriented. Higher resolution maps to determine the position angle of the radio jet in FIRST 1556+3517, if present, can clarify the situation in this individual QSO. Statistics will still be needed to determine between random lines of sight and a special line of sight.

The narrow metastable Fe II absorption lines might originate in the narrow-line region (NLR), as suggested by Halpern et al. (1996) for the broad-lined radio galaxy Arp 102B. If so, a more face-on view is required to place the NLR along the line of sight, assuming the biconical geometry common for nearby AGNs. Narrow-line emission is typically very weak

or absent from Lo-BAL QSOs (Turnshek et al. 1997; Boroson & Meyers 1992), but this could be the result of geometric effects. Netzer & Laor (1993) proposed dusty NLR clouds with anisotropic emission. If dusty NLR clouds are the metastable absorbers, they could also account for the reddening.

4. Summary

We have shown that FIRST 0840+3633 and FIRST 1556+3517 are highly polarized BAL QSOs, with the continuum polarization rising steeply toward shorter wavelengths while keeping a constant position angle in the continuum. Scattering is the likely polarization mechanism in both, with the effects of some combination of dust and dilution leading to the wavelength dependences seen. FIRST 0840+3633 shows unpolarized emission lines and increasing polarizations in its BAL troughs, but complex polarization behavior across its narrow metastable troughs. FIRST 1556+3517 shows the highest continuum polarization of any BAL QSO yet examined, emission lines polarized the same as the continuum, and unpolarized absorption troughs. While our spectropolarimetry alone cannot discriminate among the possible lines of sight to these BAL QSOs, the combination of a polarization position angle with future high-resolution radio mapping may help determine their geometry.

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Fig. 1.— FIRST 0840+3633. The top abscissa shows rest-frame wavelengths, while the bottom abscissae show observed-frame wavelengths in Å. The binning is 10 Å. The top panel is the total flux spectrum (in $\text{ergs s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$), and several absorption and emission lines are labeled (see Hazard et al. 1987 and Wampler et al. 1995 for detailed identifications in Q 0059–2735). The second panel down shows the polarization (the positive definite bias is negligible). The third panel is the polarization position angle in degrees. The bottom panel shows the polarized flux, the product of the top two panels. Error bars are 1σ .

Fig. 2.— FIRST 1556+3517. The axes are the same as in Figure 1, except that the polarization given is the Stokes Q' (Q in the rotated coordinate frame for which Q is aligned with the continuum position angle), and the polarized flux is the Stokes flux: Q' multiplied by the total flux. The binning is 10 Å, and error bars are omitted.

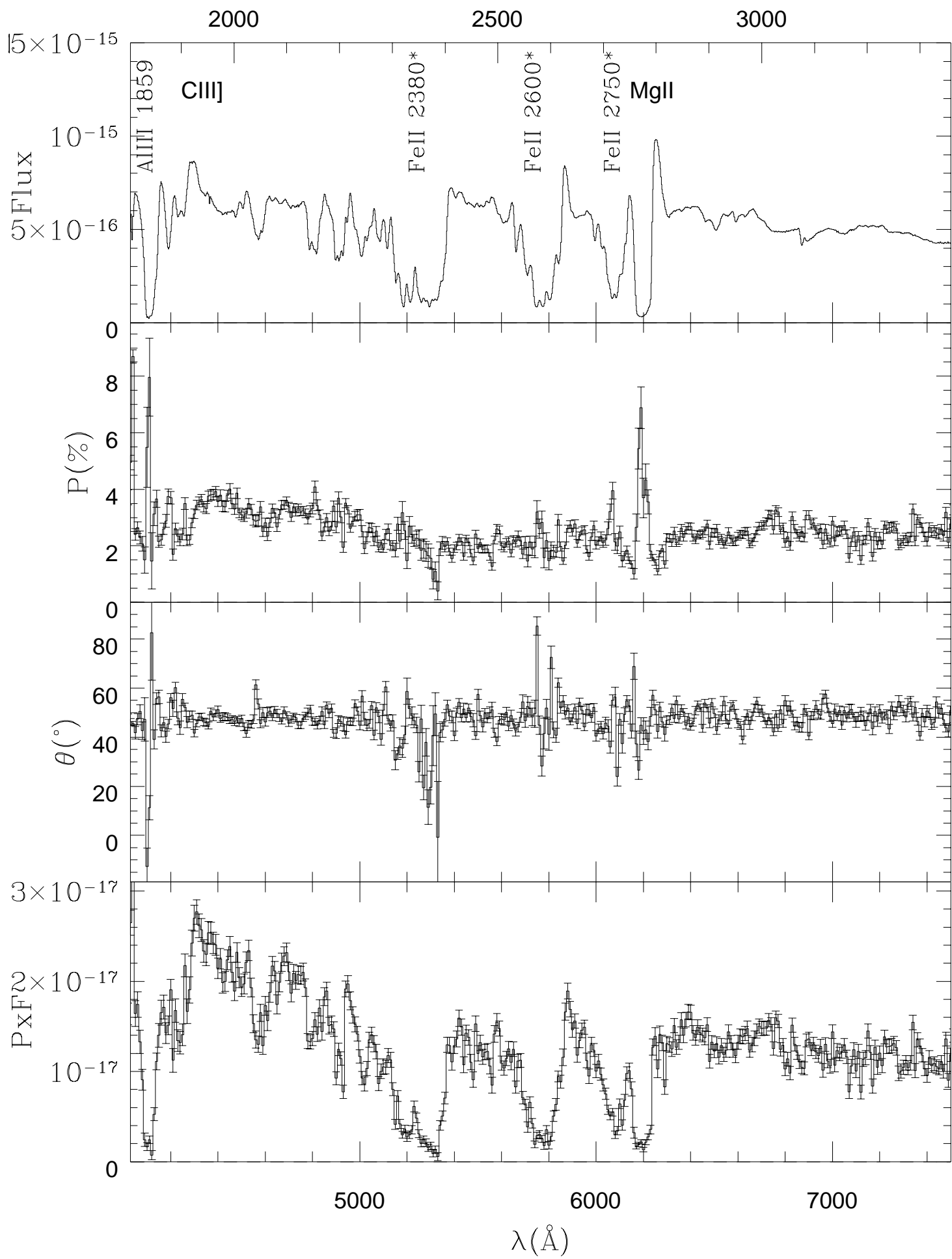


TABLE 1
“CONTINUUM” POLARIZATIONS

FIRST 0840+3633		FIRST 1556+3517	
Obs. λ range (\AA)	Rest λ_c (\AA)	Obs. λ range (\AA)	Rest λ_c (\AA)
Polarization (%)	P. A. ($^\circ$)	Polarization (%)	P. A. ($^\circ$)
4250–4800	2022	4700–5200	1982
3.21 \pm 0.05	48.0 \pm 0.4	12.1 \pm 0.2	153.6 \pm 0.6
4800–5100	2212	6000–6300	2463
2.74 \pm 0.06	47.4 \pm 0.7	6.8 \pm 0.2	152.7 \pm 0.9
5400–5600	2458	7000–8000	3003
1.96 \pm 0.06	47.7 \pm 0.9	7.1 \pm 0.1	152.3 \pm 0.3
6400–7000	2994	8000–8700	3344
2.45 \pm 0.04	49.0 \pm 0.4	6.4 \pm 0.1	152.8 \pm 0.5
7000–8000	3351		
2.44 \pm 0.04	48.9 \pm 0.4		
8000–9000	3798		
2.44 \pm 0.06	51.9 \pm 0.7		

